Applied Energy 179 (2016) 413–425

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A review of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility

Zicheng Bi[a,1], Tianze Kan[b,c,1], Chunting Chris Mi[b], Yiming Zhang[d], Zhengming Zhao[d], Gregory A. Keoleian[a,*]

[a] *Center for Sustainable Systems, School of Natural Resources and Environment, University of Michigan, 440 Church St., Ann Arbor, MI 48109, United States*
[b] *Department of Electrical and Computer Engineering, San Diego State University, 5500 Campanile Dr., San Diego, CA 92182, United States*
[c] *Department of Electrical and Computer Engineering, University of California at San Diego, 9500 Gilman Dr., La Jolla, CA 92093, United States*
[d] *State Key Laboratory of Power System, Department of Electrical Engineering, Tsinghua University, No. 1 Qinghuayuan, Beijing 100084, China*

HIGHLIGHTS

- Reviewed technology advances and sustainability performance of WPT for EVs.
- Identified the technical bottlenecks for improving system performance.
- Highlighted system performance of case studies and real-world demonstrations.
- Evaluated energy, environmental, economic, and societal impacts of WPT deployment.
- Defined WPT challenges and opportunities for enhancing future sustainable mobility.

ARTICLE INFO

Article history:
Received 19 February 2016
Received in revised form 30 June 2016
Accepted 1 July 2016

Keywords:
Wireless power transfer
Sustainability
Electric vehicle
Wireless charging
Environmental impact
Energy efficiency

ABSTRACT

Wireless power transfer (WPT), which transmits power by an electromagnetic field across an intervening space, provides the prospect of new opportunities for electric vehicles (EVs) to enhance sustainable mobility. This review article evaluates WPT technology for EV applications from both technical and sustainability perspectives. The objectives of this review include: (1) to present the state-of-the-art technical progress and research bottlenecks in WPT development and applications in the transportation sector; (2) to characterize the demonstrations of the real-world deployment of WPT EV systems; and (3) to evaluate the sustainable performance and identify challenges and opportunities for improvement. From the technical perspective, progress on coil design, compensation topologies, and power electronics converters and control methods are reviewed with a focus on system performance. From the sustainability perspective, performance is defined in terms of energy, environmental, and economic metrics, and policy drivers and issues of health and safety are also examined.

Contents

---

* Corresponding author.
E-mail address: gregak@umich.edu (G.A. Keoleian).

[1] Equal contribution from these authors.

http://dx.doi.org/10.1016/j.apenergy.2016.07.003

1. Introduction

A century ago, Nicola Tesla conducted experiments to transfer power wirelessly [1,2]. In recent decades, wireless power transfer (WPT) has been an area of intensive research to facilitate the penetration of electric products into our lives. Typical examples include wireless charging cell phones, electric vehicles (EVs), implanted medical devices, robots, and home electronic appliances. The power is typically transferred via an electromagnetic field (EMF). The widespread applications and increasing demand for WPT stems from its inherent convenience and possibility of seamless operation without charging downtime that are otherwise two major problems for wired chargers. Based on the working principles, WPT can be categorized as (1) electromagnetic radiation (microwave or laser) WPT that is applicable for long-distance power transmission, such as transmission between solar power satellites and the earth, (2) electric induction/coupling WPT (also known as capacitive coupling WPT) that is for near field transmission, and (3) magnetic coupling WPT (inductive or resonant) that is also for near field transmission but does much less harm to the human body than electric induction/coupling WPT due to the intensity of the electric field [3,4]. Extensive work [3,5–8] has been done on magnetic coupling WPT for EV charging applications, which is the focus of this review. In terms of working modes, WPT can be classified as either (1) static or stationary WPT: charge while the vehicle is not in motion; or (2) dynamic WPT: charge while the vehicle is moving along the WPT-enabled roadway.

WPT for EVs has the potential to overcome the drawbacks of wired chargers and eliminate some hurdles toward vehicle electrification and sustainable mobility [9]. Aside from its convenience compared to wired chargers, WPT can enable significant downsizing of the onboard EV battery. Take the stationary WPT for electric transit buses as an example where the onboard rechargeable battery can be downsized by at least two thirds [10,11] due to the frequent "opportunity charges" while loading and unloading passengers at bus stations during bus operation. Attributable to these charges en route, it is reasonable to carry a much smaller onboard battery while still fulfilling the vehicle route requirements. This results in a substantial vehicle weight reduction given that the battery pack can comprise about a quarter of the weight of an all-electric transit bus for sustaining day-long operation [12]. Battery downsizing has significant implications for lightweighting the vehicle and improving the fuel economy [10]. In the scenario of dynamic WPT for passenger cars on major roadways, ubiquitous charging infrastructure would theoretically allow EVs to have unconstrained range and a minimal capacity of onboard battery [13]. Nevertheless, WPT for EVs poses additional sustainability trade-offs and concerns that have stimulated discussion in academia and industry. The trade-off is on the burden of large-scale WPT infrastructure deployment versus the benefits of battery downsizing and fuel economy improvement. The concern is on the technical and economic feasibility of dynamic WPT and the decrease in charging performance when the vehicle is moving at high speeds.

This review article summarizes both the most up-to-date technical advances of WPT technology for EV applications and the state of sustainability assessments of WPT EV systems. It presents current research highlights, gaps, challenges, and opportunities of WPT technology for EVs from both the technical and sustainability perspectives. The article first introduces the fundamental theory of WPT and reviews the technical advances and challenges for both stationary and dynamic WPT. The second part highlights selected case studies of WPT applications. The third part summarizes the discussions on the sustainability, safety, and social implications of WPT technology, identifies challenges and opportunities for improving performance, and provides prospects to enhance sustainable mobility.

2. State-of-the-art research and technology development

Fig. 1 shows a non-ionizing radiative wireless charging system for EVs through near-field magnetic coupling. The alternating current (AC) utility power first goes through the electromagnetic interface (EMI) stage, and then gets rectified and boosted to direct current (DC) power with a power factor of nearly 1.0 (0.95–0.98 in most cases), which is similar to a conductive charging system [14]. The voltage of the DC power is decreased by the BUCK stage. The BUCK stage can tune its output voltage to range from 0.03 to 0.97 of its input voltage, which achieves "soft" start/stop of the charger and continuous tuning of its output power. Here, the buck stage is optional since alternatively a pre-charge circuit, which is composed of two contactor relays and one resistor, is able to help achieve "soft" start of the charger and a phase-shift method can be used in the inverter stage to ensure the low power operation and "soft" stop of the charger. This combination of a pre-charge circuit and phase-shift method instead of a buck stage may reduce the system efficiency, but it will lower the total cost and volume of a wireless charging system. In the inverter stage, the DC power is converted to high frequency AC power, which then resonates in the primary compensation network and the primary coil, with the resonant frequency adjusted to the switching frequency of the inverter. The secondary coil receives the high frequency AC power wirelessly through the mutual inductance between the primary and secondary coils. The secondary compensation network, together with the secondary coil, is required to be tuned to have the same resonant frequency in order to maximize the transfer efficiency. The high frequency AC power is then rectified to DC power through the rectifier stage and filtered by the filter network. Finally, the DC power is available to charge the battery pack.

Research into wireless charging systems is mainly focused on three areas: (1) coil design; (2) compensation topologies; and (3) power electronics converters and control methods.